

Exploring the Edge of the Stellar Universe with Gamma-ray Observations

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Abstract. The determination of the densities of intergalactic photons from the FIR to the UV produced by stellar emission and dust reradiation at various redshifts can provide an independent measure of the star formation history of the universe. Using recent *Spitzer* and *GALEX* data in conjunction with other observational inputs, Stecker, Malkan and Scully have calculated the intergalactic photon density as a function of both energy and redshift for $0 < z < 6$ and for photon energies from 0.003 eV to the Lyman limit cutoff at 13.6 eV in a Λ CDM universe with $\Omega_\Lambda = 0.7$ and $\Omega_m = 0.3$. Their results are based on backwards evolution models for galaxies developed previously by Malkan and Stecker. The calculated background SEDs at $z = 0$ are in good agreement with present observational data and limits. The calculated intergalactic photon densities were used to predict the absorption of high energy γ -rays in intergalactic space from sources such as blazars and quasars, this absorption being produced by interactions of the γ -rays with intergalactic FIR-UV photons having the calculated densities. The results are in excellent agreement with absorption features in found in the very high energy γ -ray spectra of the low- z blazars, Mrk 421 and Mrk 501 at $z = 0.03$ and PKS 2155-304 at $z = 0.12$. However, uncertainties in the predicted γ -ray absorption features grow with redshift. Actual measurements of the spectra of γ -ray sources at higher redshifts from detectors such as the (soon to be launched) *GLAST* space telescope can be used to determine intergalactic photon densities in the distant past, thereby shedding light on the history of star formation and galaxy evolution.

1. Introduction

Most of this meeting has involved the use of deep astronomical surveys to study the formation and evolution of galaxies and stars in their youngest phases at high redshifts through direct observations of galaxies at wavelengths ranging from the radio and submillimeter to the X-ray range. In this paper, I will discuss a complementary approach which hinges on the determination of “historical” intergalactic IR, optical, and UV photon densities produced by the emission of stars and the reradiation of dust in these young galaxies in the distant past. The energy distribution and densities of these intergalactic photons then become a measure of the *total* star production and population distributions at high redshifts from all galaxies, visible and obscured, observed and unobserved.

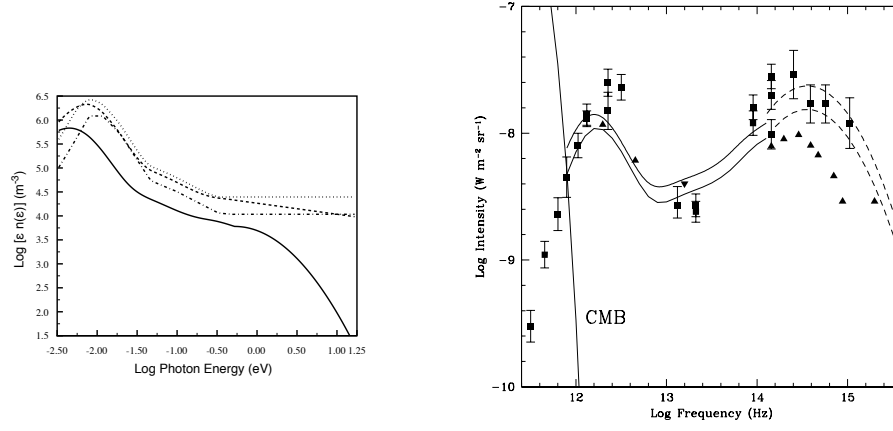


Figure 1. The photon density $e n(\epsilon)$ as a function of energy for various redshifts based on the fast evolution model. Solid line: $z = 0$, dashed line: $z = 1$, dotted line: $z = 3$, dot-dashed line: $z = 5$. (from SMS)

Figure 2. Spectral energy distribution of the diffuse background radiation at $z = 0$ from SMS. Error bars show data points, triangles show lower limits from number counts, and the inverted triangle shows an upper limit from Stecker and De Jager (1997). The upper and lower solid lines show the SMS fast evolution and baseline evolution predictions, and the dotted lines show their extensions into the optical-UV, based on the results of Salamon and Stecker (1998).

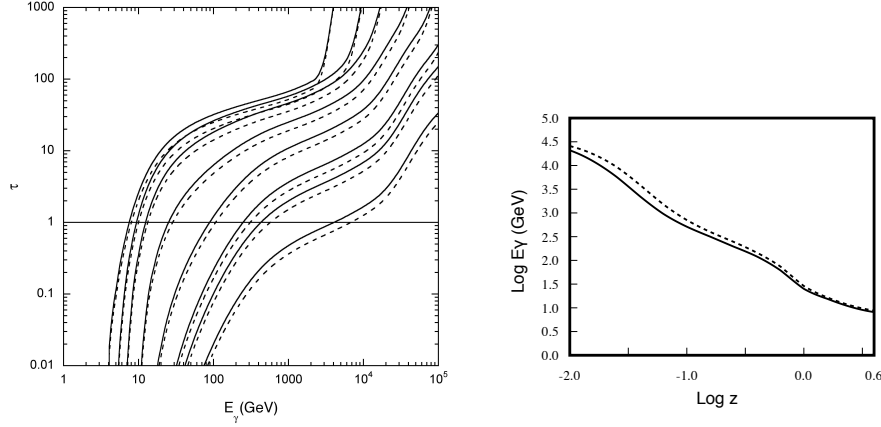


Figure 3. The optical depth of the universe to γ -rays from interactions with intergalactic photons, given as a function of energy for a family of redshifts from bottom to top of 0.03, 0.117, 0.2, 0.5, 1.0, 2.0, 3.0 and 5.0. Fast evolution model: solid lines, baseline model: dashed lines. (from SMS)

Figure 4. The critical optical depth $\tau = 1$ as a function of γ -ray energy and redshift for the fast evolution (solid curve) and baseline (dashed curve) models. Areas to the right and above these curves correspond to the region where the universe is optically thick to γ -rays. (from SMS)

2. Zeroth Order Model Calculations

As a zeroth order approximation to the expected intergalactic absorption at high redshifts, we take the results of backward evolution models of Stecker, Malkan and Scully (2006), hereafter called SMS. These models are based on two plausible cases of pure luminosity evolution, *viz.*:

(1) In the more conservative “baseline” scenario, all $60\mu\text{m}$ galaxy luminosities evolved as $(1+z)^{3.1}$ with their evolution stopped at $z_{\text{flat}} = 1.4$ and galaxy luminosities assumed constant (nonevolving) at the higher redshifts $1.4 < z < 6$, with negligible (assumed zero) emission for $z > 6$. This later assumption is supported by the recent *Hubble* deep survey results indicating that the average star formation rate is dropping off significantly at a redshift of 6 (Bunker *et al.* 2004; Bouwens *et al.* 2005). Independent evidence from luminosity functions of Lyman break galaxies at redshifts from 3 to 6 indicates a similar decrease in the star formation rate (Shimasaku *et al.* 2005). However, it is important to note that the star formation rate for $z > 6$ is *not* zero and this will modify the results of SMS so that the predicted γ -ray opacity of the high redshift universe will be somewhat different, depending on the real star formation rate of the universe at redshifts greater than 6.

(2) A “fast evolution” scenario where galaxy luminosities evolved as $(1+z)^4$ for $0 < z < 0.8$ and evolved as $(1+z)^2$ for $0.8 < z < 1.5$ with no evolution (all luminosities assumed constant) for $1.5 < z < 6$ and, again, zero luminosity is assumed for $z > 6$. This evolution model is based on the mid-IR luminosity functions recently determined out to $z = 2$ by Perez-Gonzalez *et al.* (2005). The “fast evolution” picture is favored by recent *Spitzer* observations (Le Floch *et al.* 2005, Perez-Gonzalez *et al.* 2005). It provides a better description of the deep *Spitzer* number counts at $70\mu\text{m}$ and $160\mu\text{m}$ than the “baseline” model. However, *GALEX* observations indicate that the evolution of UV radiation for $0 < z < 1$ may be somewhat slower and more consistent with the “baseline” model within errors (Schiminovich *et al.* 2005). Also, the baseline model fits the $24\mu\text{m}$ *Spitzer* source counts more closely than the fast evolution model. The *Spitzer* IRAC (Infrared Array Camera) counts lie in between the predictions of these two models.

Figure 1 shows the resulting photon density $\epsilon n(\epsilon)$ as a function of energy at various redshifts for the fast evolution model. Figure 2 shows the predicted background SEDs compared with the data and empirical limits (see, *e.g.*, Hauser and Dwek 2001).

3. The Optical Depth of the Universe to Gamma Rays

Quantum electrodynamics shows that two photons can annihilate to produce an electron-positron pair provided that the total energy in the center of momentum system of the interaction is above the threshold for making an electron and a positron (Breit and Wheeler 1934). The cross section for this interaction peaks close to the threshold energy (Jauch and Rohrlich 1955). This results in a redshift “horizon” for γ -rays, beyond which the universe is opaque (Stecker 1969; Fazio and Stecker 1970). The SMS results on the optical depth as a function of energy for various redshifts out to a redshift of 5 are shown in Figure 3. Figure

4 shows the energy-redshift relation giving an optical depth $\tau = 1$ based on the SMS calculations of $\tau(E_\gamma, z)$.

As is shown in Figure 3, for γ -ray sources at the higher redshifts there is a steeper energy dependence of $\tau(E_\gamma)$ near the energy where $\tau = 1$. This effect is caused by the sharp drop in the UV photon density at the Lyman limit. There will thus be a sharper absorption cutoff in the multi-GeV γ -ray spectrum of sources at high redshifts than in the TeV spectra of more nearby γ -ray sources. It is important to note that *the exact position of this cutoff in energy is directly related to the z -dependence of the star formation rate at high redshifts.*

3.1. Implications for *GLAST*

Because absorption cutoffs in the spectra of blazars at the higher redshifts lies in the multi-GeV range, *GLAST*, the Gamma Ray Large Space Telescope (<http://glast.gsfc.nasa.gov>), to be launched in the fall of 2007, will be able to make measurements of such features and thus probe the early star formation rate (Chen, Reyes & Ritz 2004). *GLAST* will be able to detect blazars at $z \sim 2$ at multi-GeV energies, the critical energy range for the expected sharp absorption cutoffs in high redshift γ -ray sources as shown in Figure 3. Thus, γ -ray observations by *GLAST* can complement the deep galaxy surveys and help determine the redshift when significant star formation began. In fact, *GLAST* need not have to detect γ -ray sources at high redshifts in order to acquire information about the evolution of intergalactic photon fluxes. If the diffuse γ -ray background radiation is from unresolved blazars (Stecker & Salamon 1996), a hypothesis which can be independently tested by *GLAST* (Stecker & Salamon 1999), the effects of γ -ray absorption will steepen the spectrum of this radiation at γ -ray energies above ~ 10 GeV (Salamon & Stecker 1998).

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